The Tumultuous Lives of Galactic Dwarfs and The Missing Satellites Problem

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with

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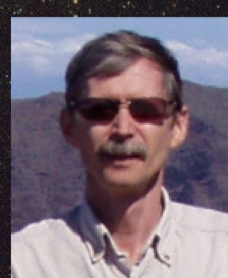
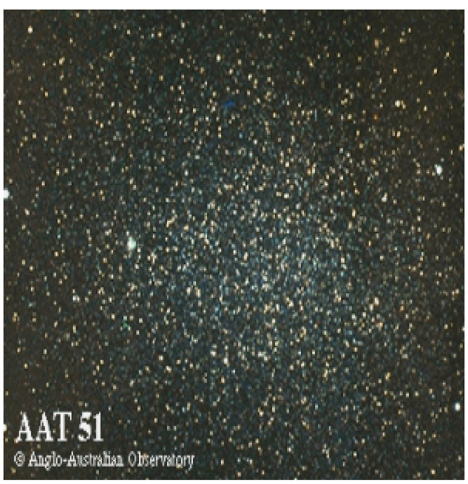


Anatoly Klypin (NMSU)

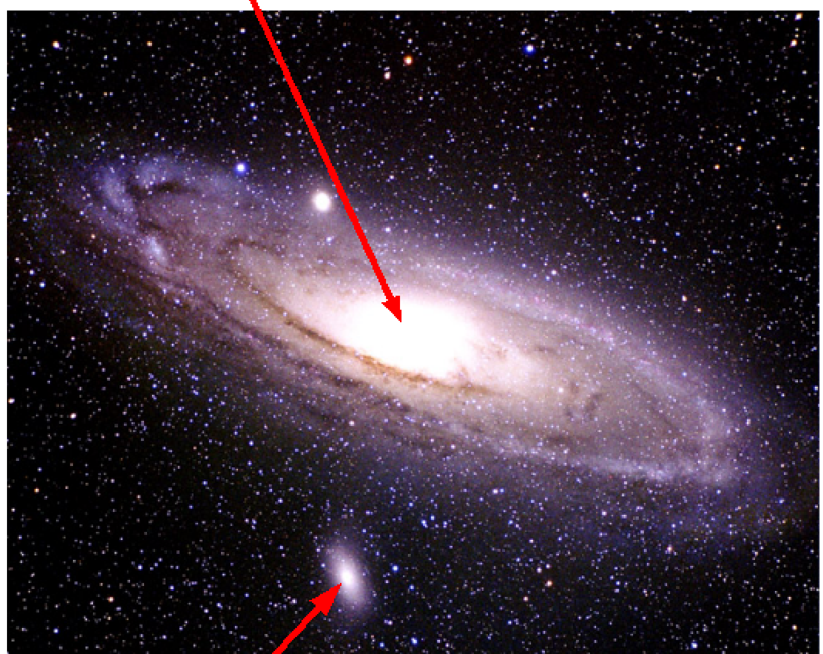
Galaxies of the neighborhood

dwarf Irregulars (dIrrs)



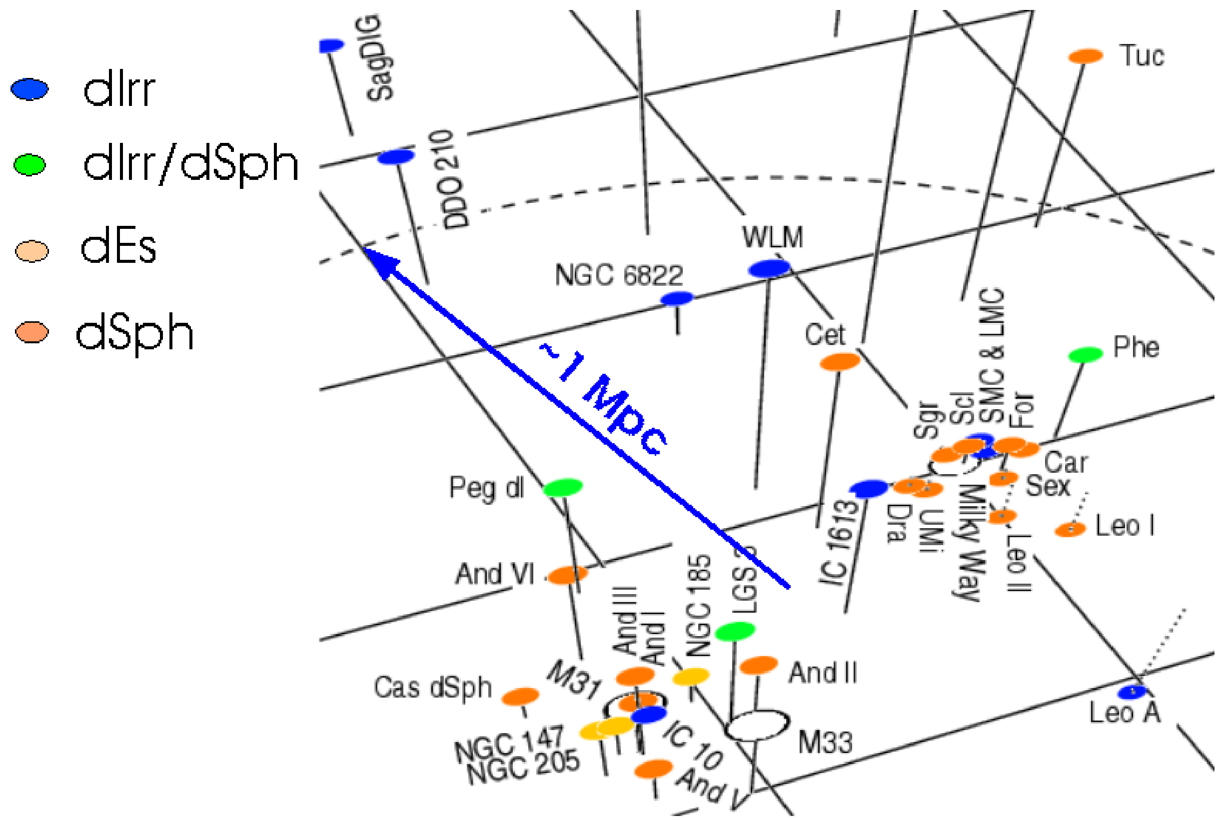
dwarf Spheroidals (dSph)

Andromeda (M31), Milky Way



dwarf Ellipticals (dEs)

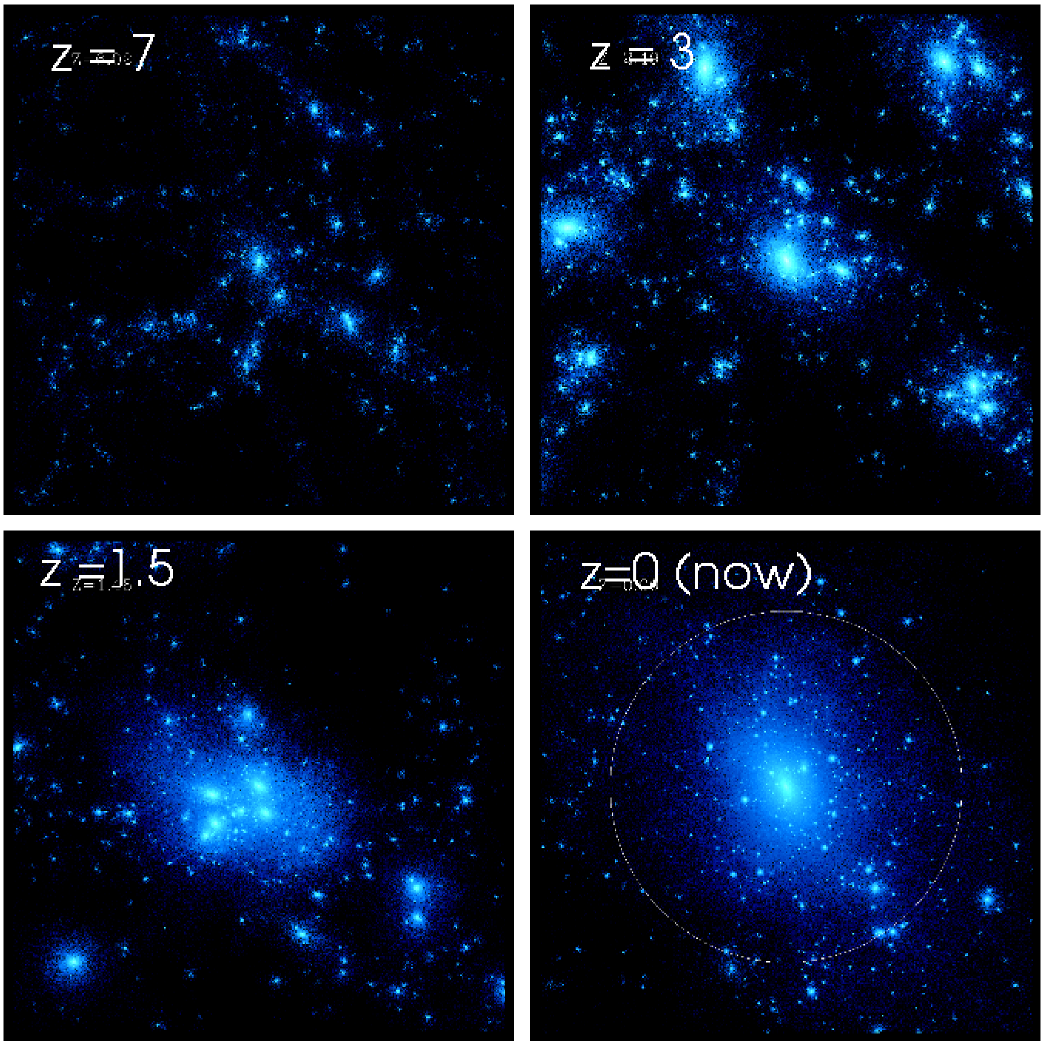
The Local Group



Grebel 1999

Hierarchical Buildup of a Milky Way halo

in a Cold Dark Matter (CDM) cosmology



$\Lambda\mathrm{CDM}$: $\Omega_0 = 0.3$; $\Omega_\Lambda = 0.7$

$h = 0.7$; $\sigma_8 = 0.9$; $n_s = 1.0$

The ART code simulation

particle mass

$m_p = 1.2\mathrm{x}10^6 h^{-1}$ Msun

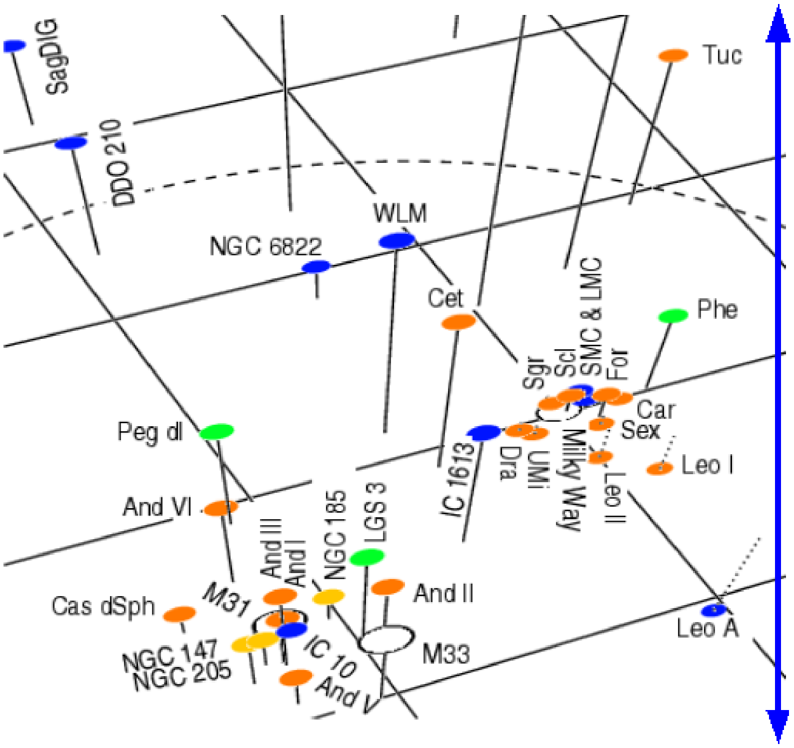
force softening:

$\varepsilon = 100 h^{-1}$ pc

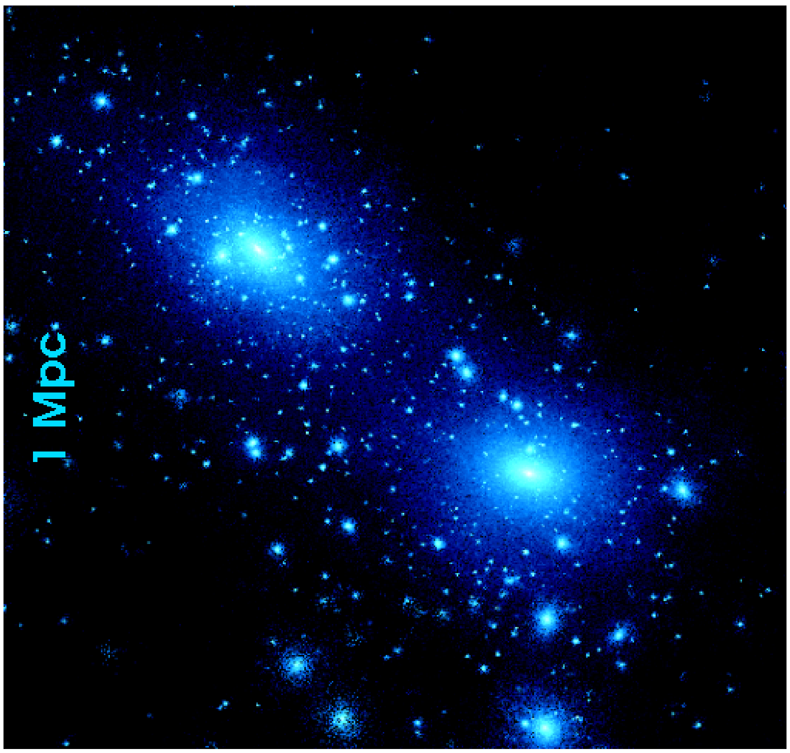
0.5 Mpc

Mvir = 2.2 x10^{12} Msun

The Missing Satellites Problem



The Local Group

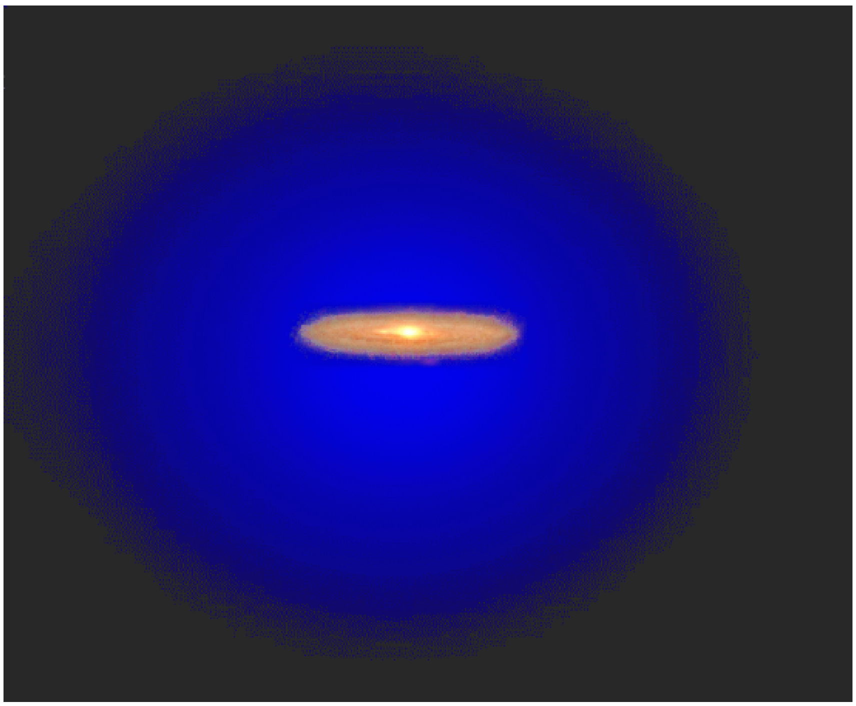


LCDM simulation

Kauffman, White & Guiderdoni 1993
Klypin, Kravtsov, Valenzuela & Prada 1999; Moore et al. 1999

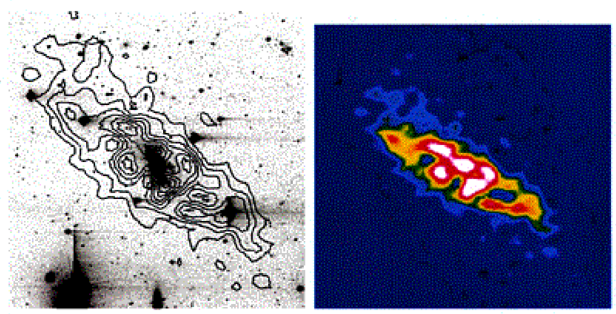
Galaxies in CDM models form in extended DM halos

(if the halo mass is right)

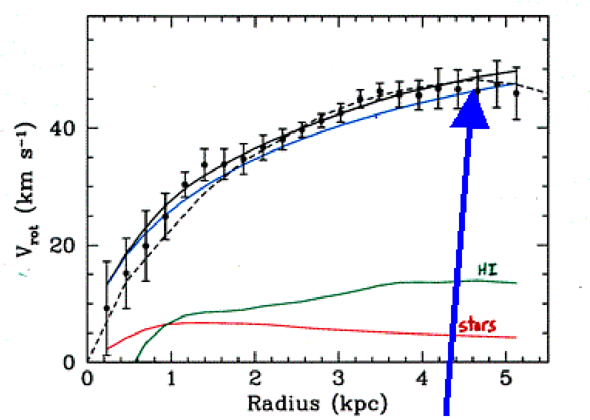


Rotation curves of dwarf galaxies are dominated by the extended DM halo

DDO 154



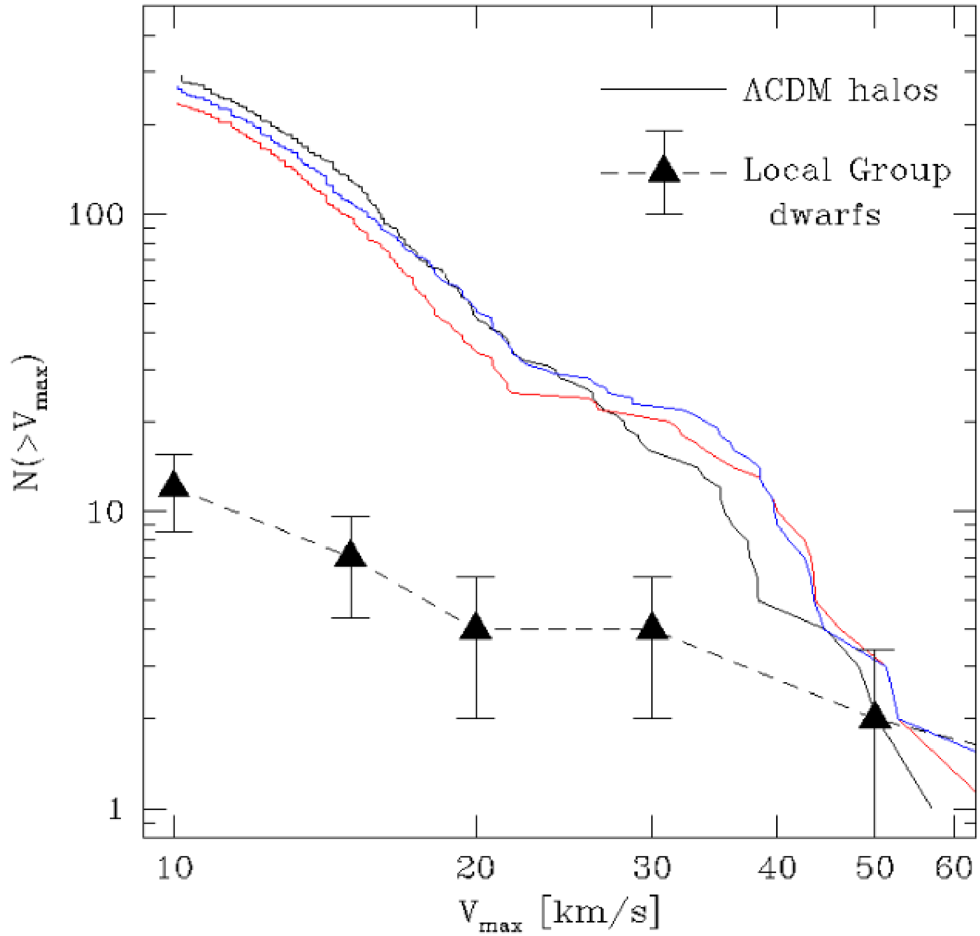
(Original HI data from Carignan & Purton, 1999)



Vmax = the max of circular velocity curve $=(GM(<r)/r)^{1/2}$

The Missing Satellites Problem quantified

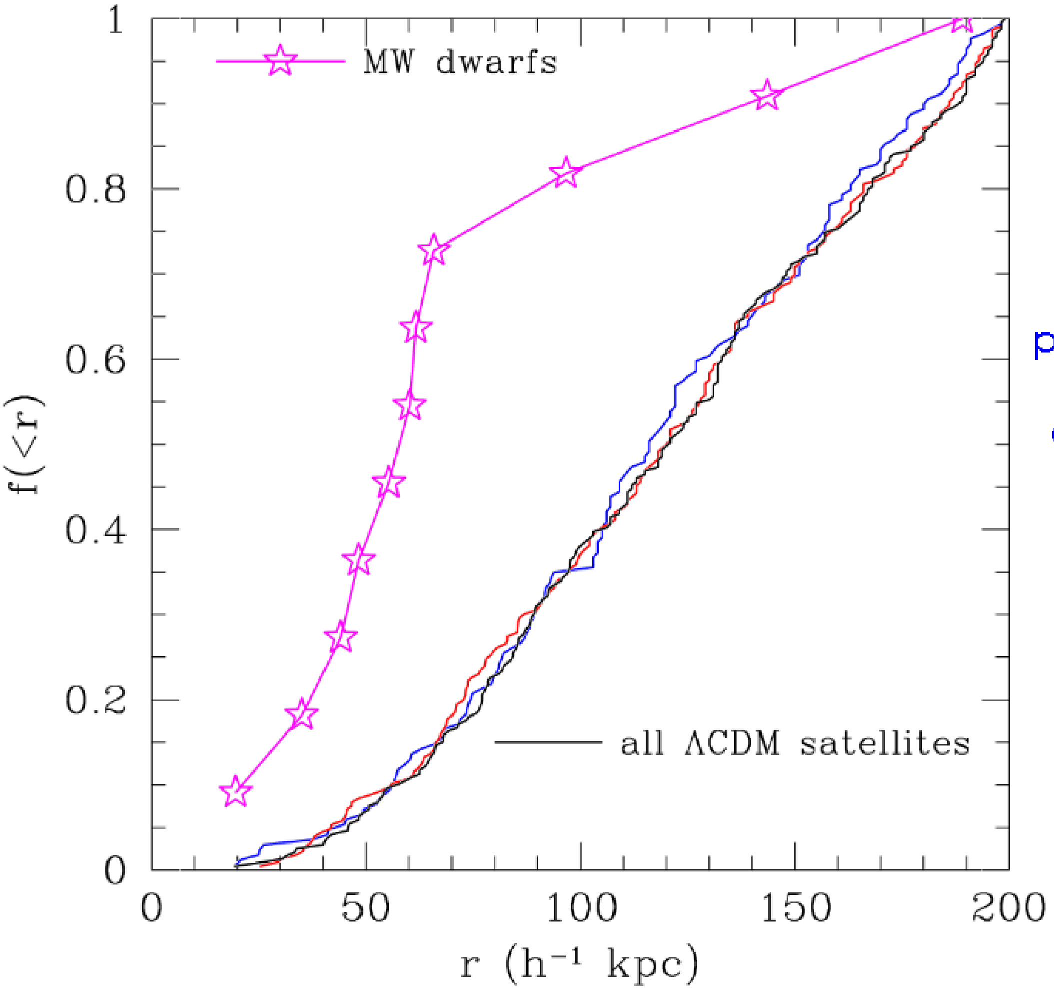
cumulative circular velocity function (CVF)



maximum circular velocity $V_{max}=(GM/r)^{1/2}$

Differences in spatial distribution

fraction of objects at distances less than r



distance to the center of the host

probability that distributions are consistent is < 0.001

Proposed modifications to CDM
(a partial list)

- Self- interacting DM (SIDM)
  Spergel & Steinhardt (1999); and followup by Ostriker(1999); Hannestad (1999); Miralda- Escude (2000); Moore et al. (2000); Hogan & Dalcanton (2000); Yoshida et al. (2000a,b); Burkert (2000); Firmani et al. (2000); Mo & Mao (2000); Kochanek & White (2000); Colin et al (2000- 02)

- Warm dark matter (WDM)
  Sommer- Larsen & Dolgov (1999); Hogan (1999); Kamionkowski & Liddle (1999); Colin et al. (1999); Bode et al.(2000); Knebe et al. (2001)

- A combination of the above
  Hannestad & Scherrer (2000)

- Fuzzy CDM (FCDM) Hu, Barkana & Gruzinov (2000)

- Repulsive DM Goodman (2000)

- Annihilating DM Medvedev (2000)

- Tited power spectra (Zentner & Bullock 2002, 2003)

Anomalous flux ratios in four image lenses may be an evidence for the CDM substructure

Mao & Schneider 1998; Metcalf and Madau 2001; Chiba 2001; Dalal & Kochanek 2001, 2003

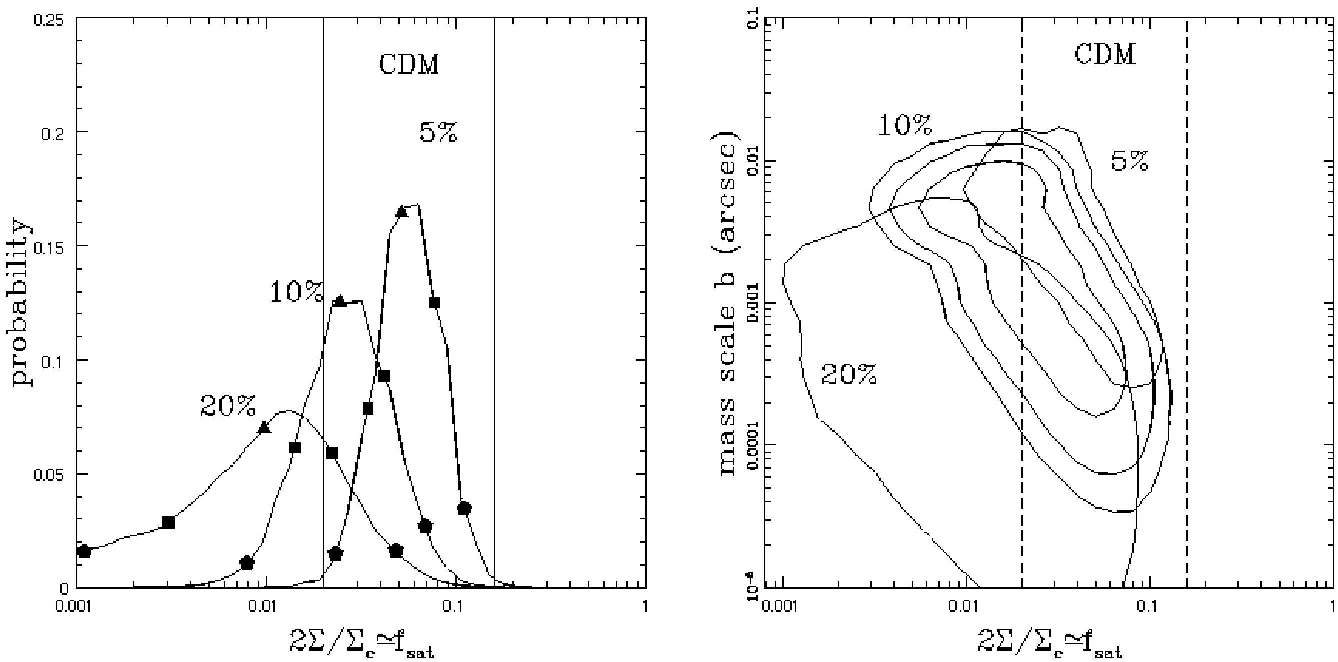
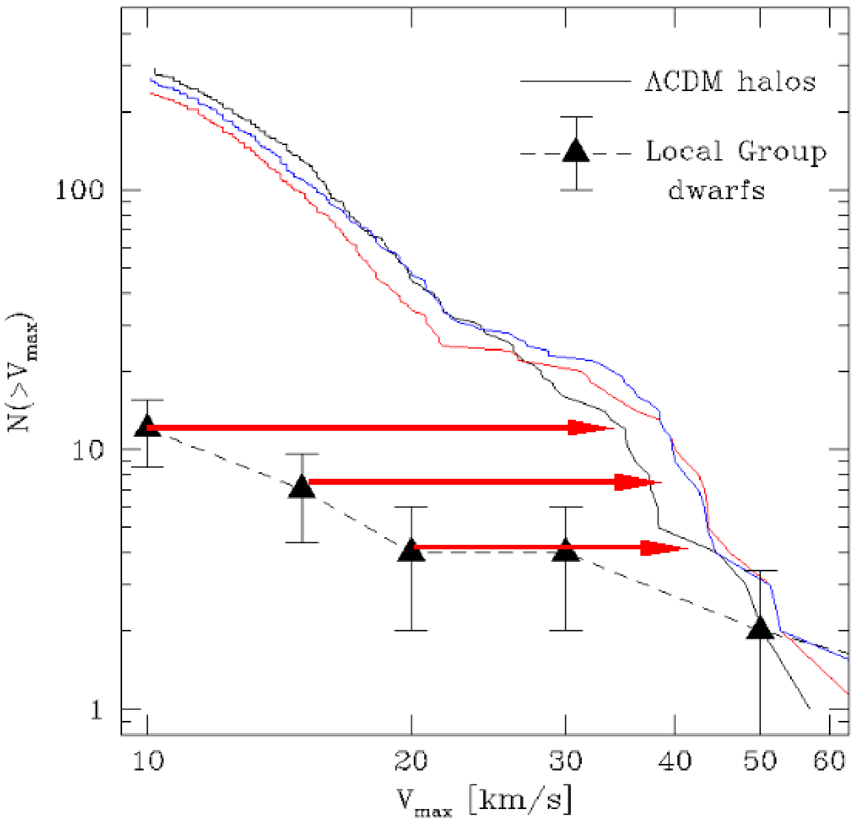


FIGURE 4. Results for the DK02 sample of 7 lenses. The left panel shows the results for estimating f_{sat} with $b = 0\farcs001$ fixed, and the right panel shows the results estimating the deflection scale b as well. Distributions are shown assuming flux measurement errors of 5%, 10% and 20%, where we adopted 10% as our standard estimate.

Selective suppression of galaxy formation or universal suppression mass scale?



maximum circular velocity

Stoehr et al. (2002, 2003) argued that circular velocities of dwarf spheroidals are larger than previously estimated and all of them have Vmax > 30- 40 km/s

This implies a well- defined suppression scale of Vmax (and mass)

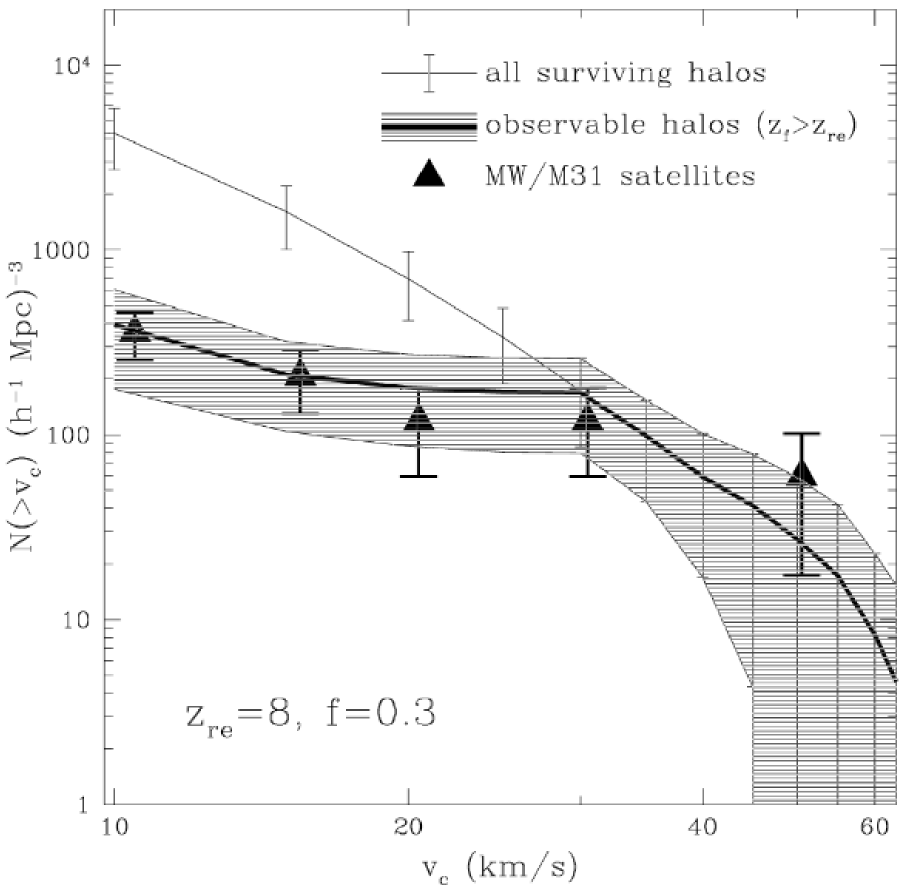
However, Kazantzidis et al (2004) dispute this and suggest that numerical effects affected results (and conclusions) of Stoehr et al.

There are other indirect arguments against Stoehr et al.'s solution of the problem

Can reionization explain the observed abundance of dwarfs?

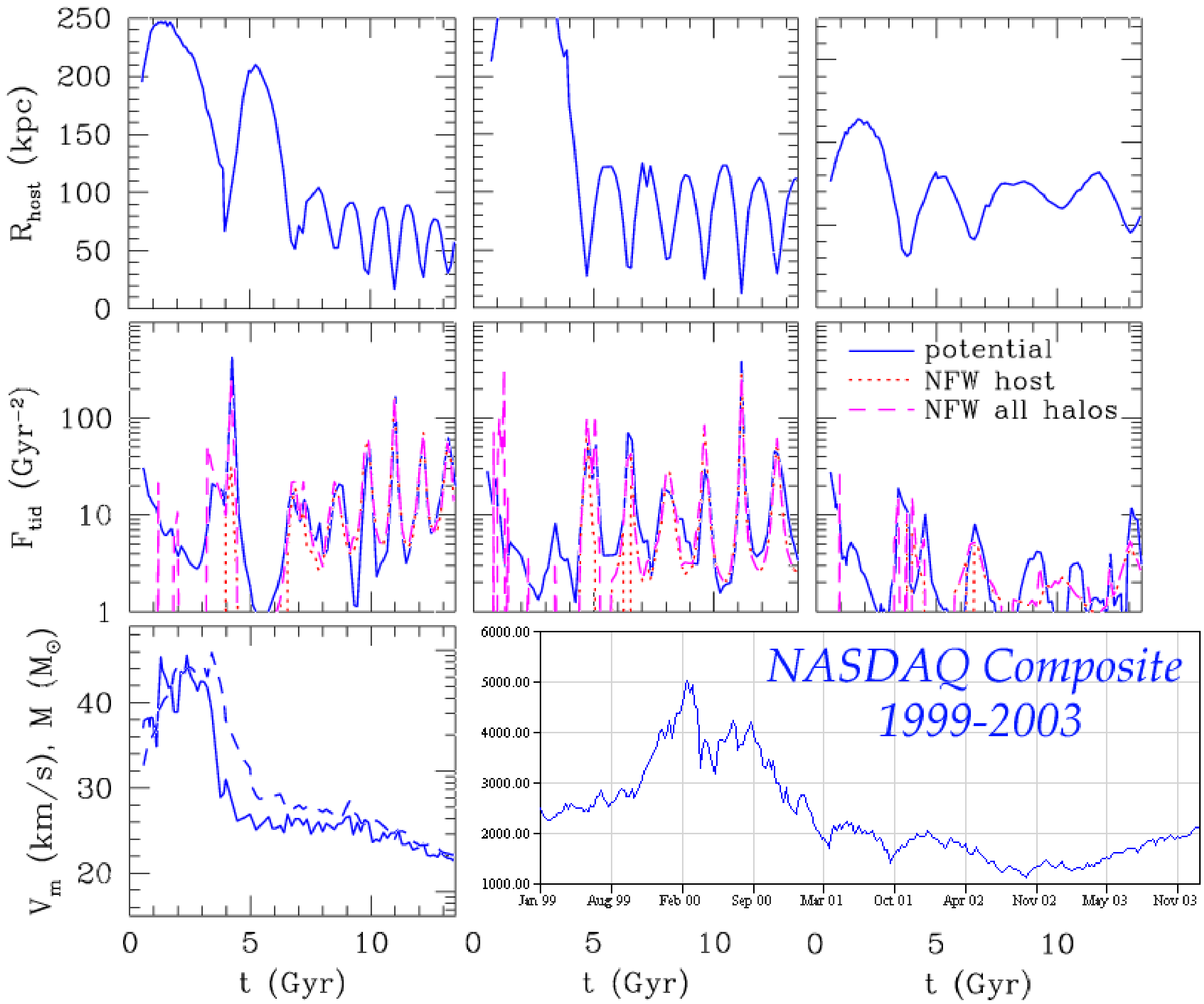
Bullock, Kravtsov & Weinberg 2000; Benson et al. 2001; Somerville 2002

Cumulative velocity function



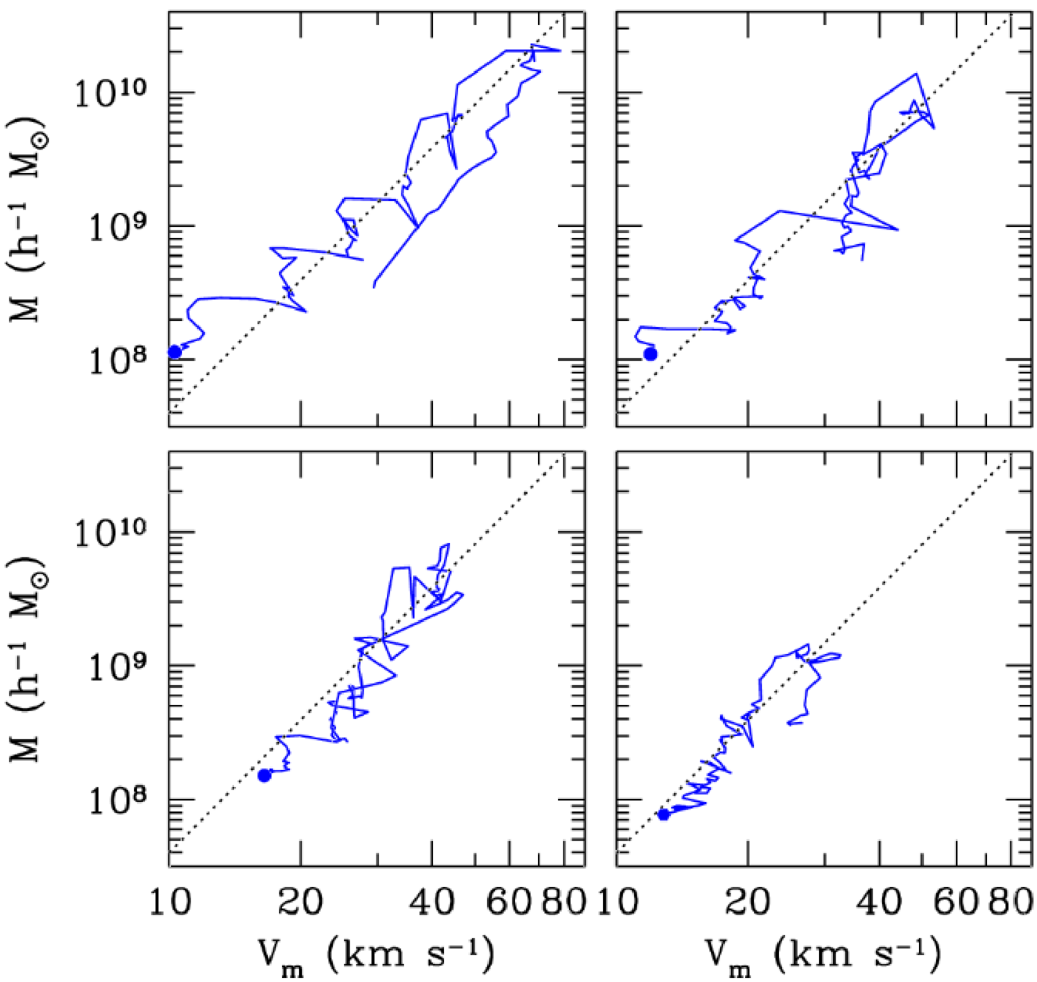
maximum circular velocity

Tumultuous lives of galactic satellites



Boom and Bust

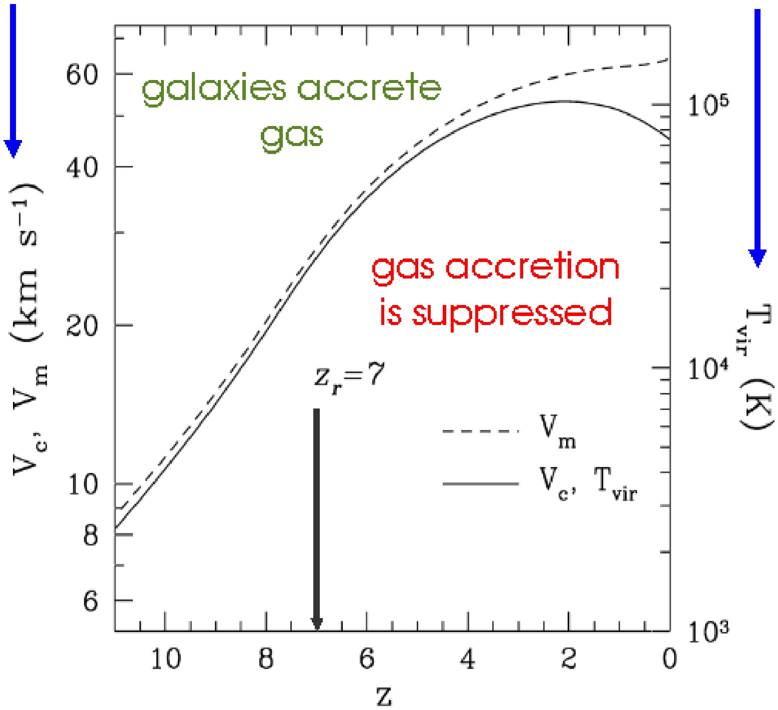
(dynamical evolution of dwarf halos in four examples)



Is every Local Group dwarf spheroidal a remnant of a high redshift LMC?

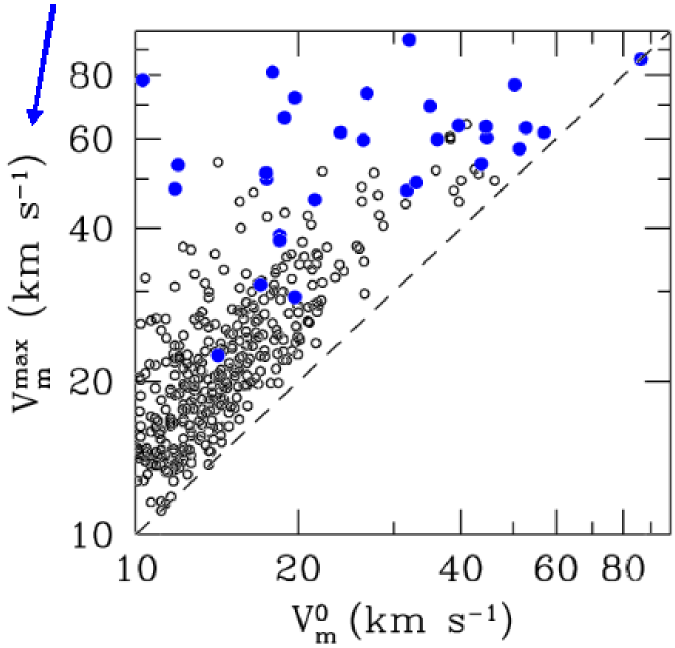
characteristic ("filtering") circular velocity

characteristic virial temperature



redshift

max circular velocity in the past



circular velocity today

N. Gnedin (2000)

A simple model of dwarf galaxy formation

❑ Use mass accretion, tidal forces, and changes of internal properties extracted for each object from numerical simulation

❑ Assume that effect of reionization and UV background can be modeled using the filtering mass formalism normalized to simulations (Gnedin 2000).

❑ Assume that gas cools and settles into an exponential disk and stars form according to the Schmidt's law. Starbursts after tidal shocks. Stars experience tidal heating.

$$\dot{\Sigma}_* \propto \Sigma_g^{1.4}, \quad \text{for} \quad \Sigma_g > \Sigma_{\rm th} = 5 \ M_\odot \, {\rm pc}^{-2}$$

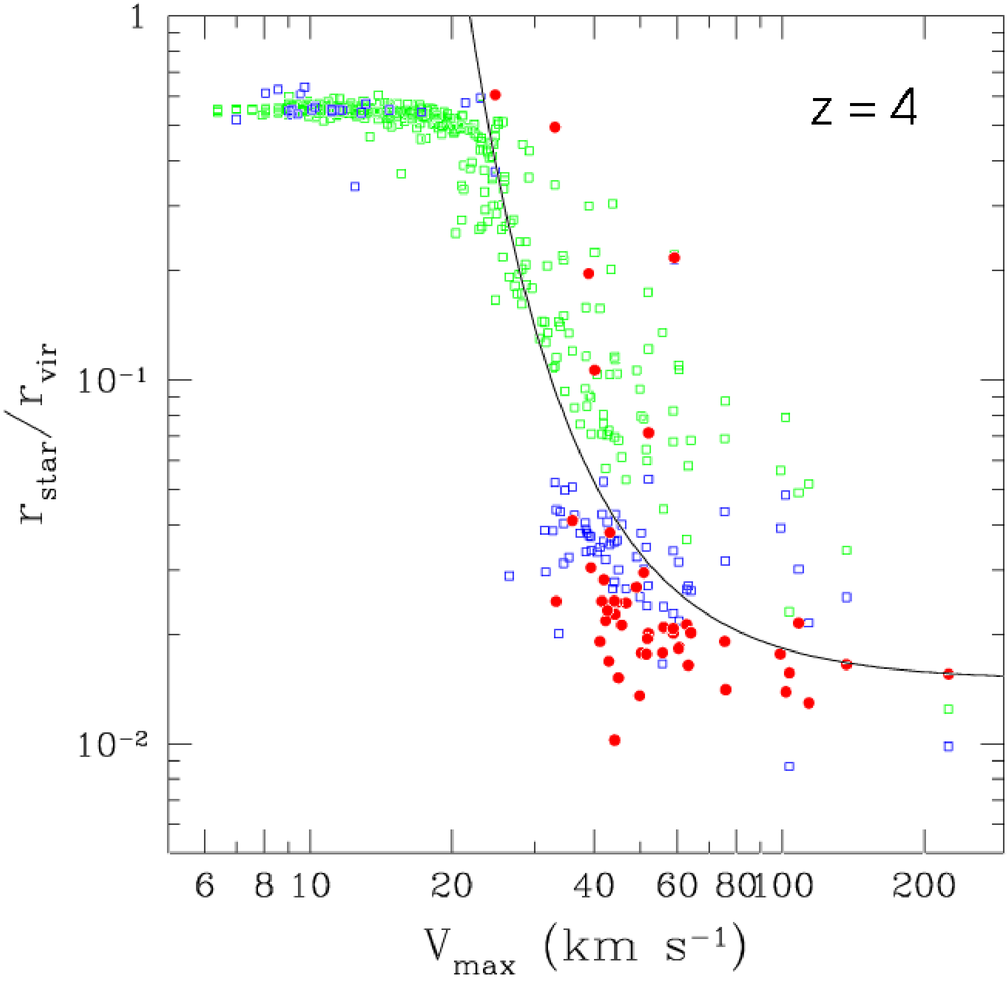
❑ Assume that cooling of gas becomes inefficient in halos with the virial temperature of Tvir < 10^4 K or Vmax < 20- 30 km/s

$$r_{\rm d} = 2^{-1/2} \lambda \, r_{\rm vir} \times e^{10(V_4/V_{\rm m})^2}$$

This is a key piece of the model

Inefficiency of gas cooling in dwarf halos

ratio of stellar extent to the halo extent



maximum circular velocity

line is the model assumption

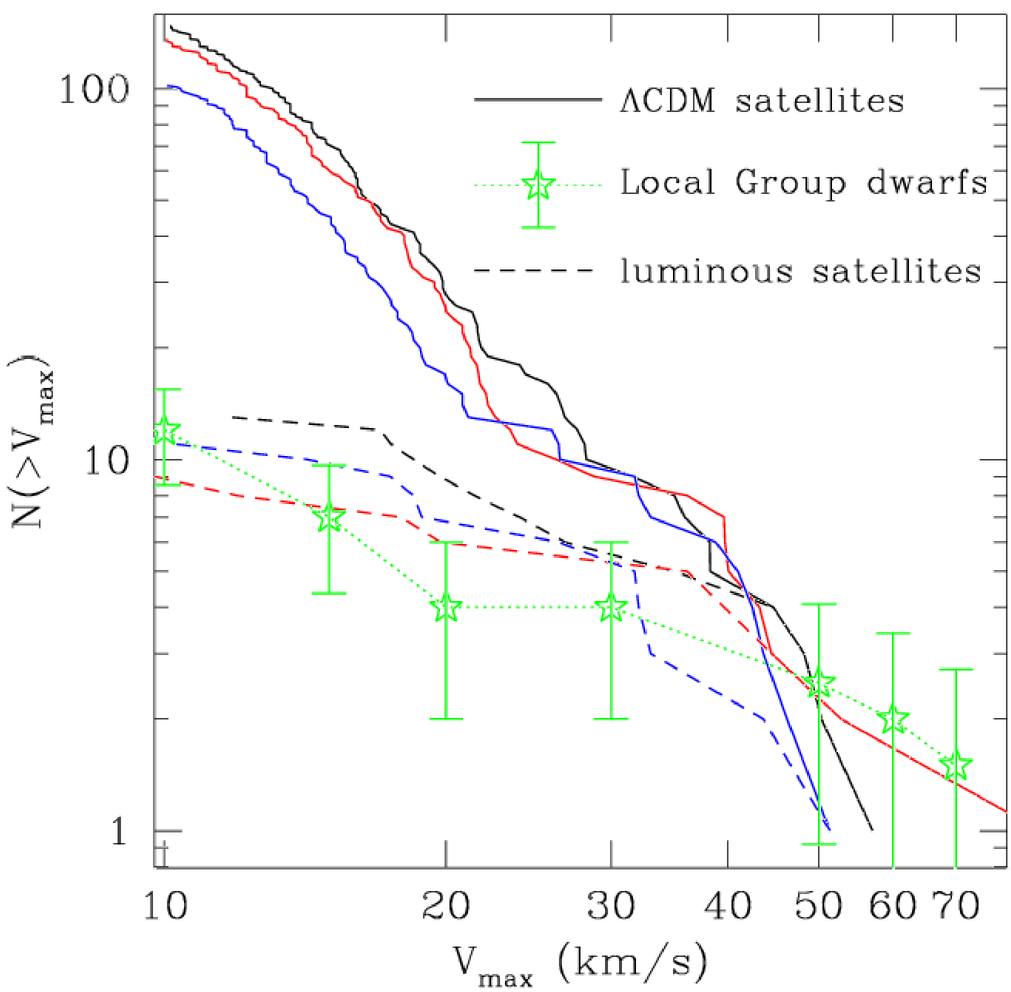
points are simulation:

red = stars

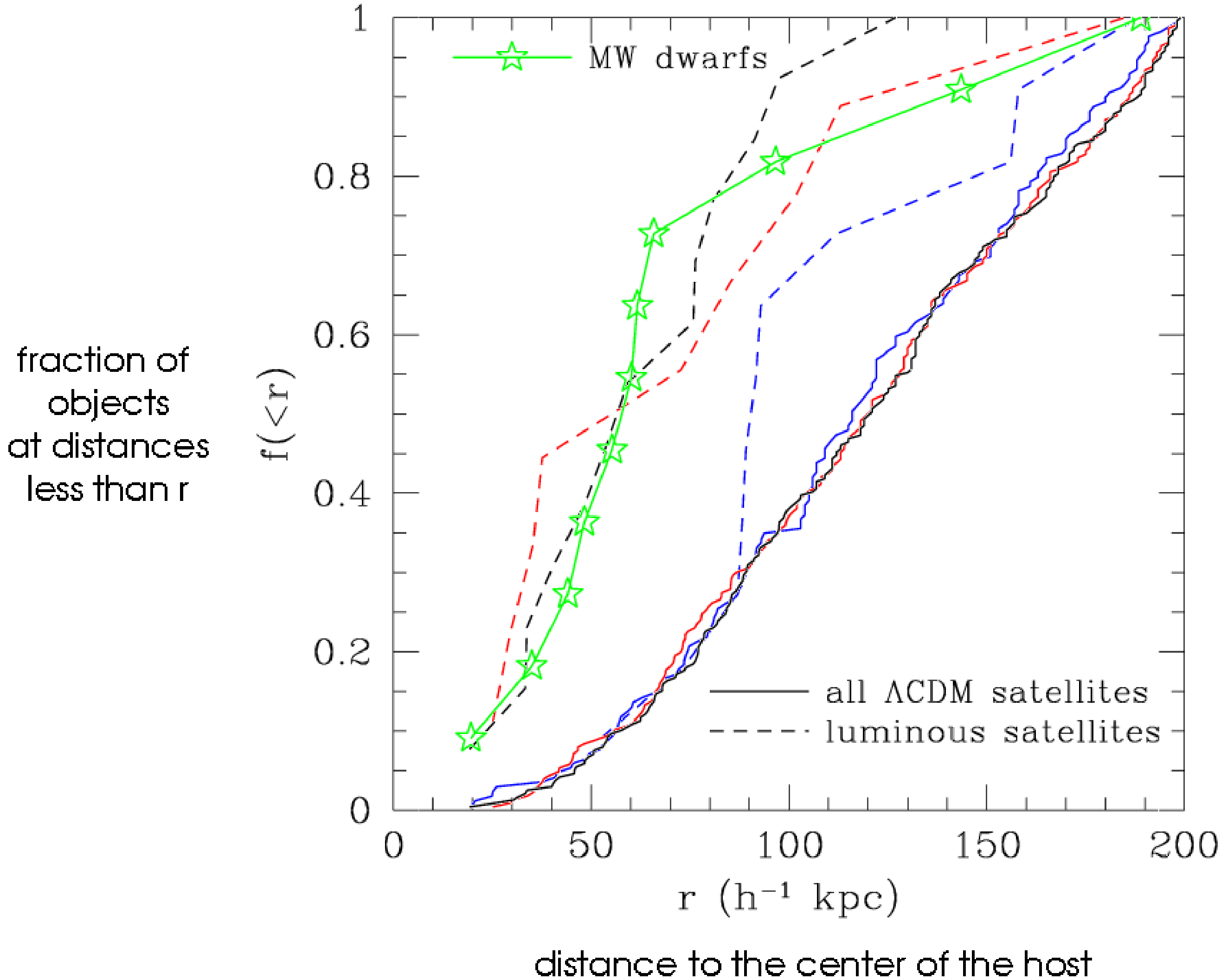
blue = cold gas

green = all gas

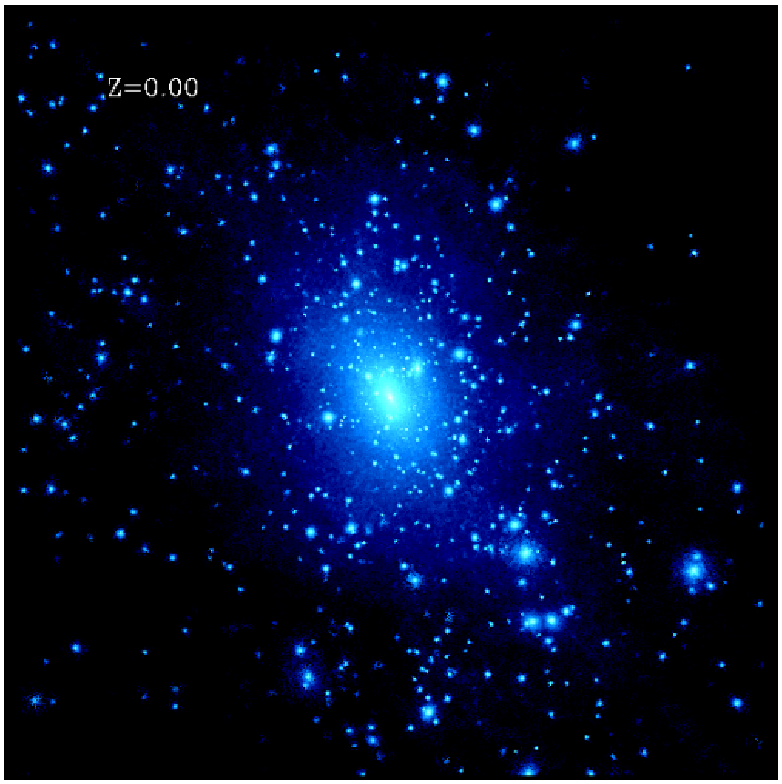
Velocity function of luminous satellites



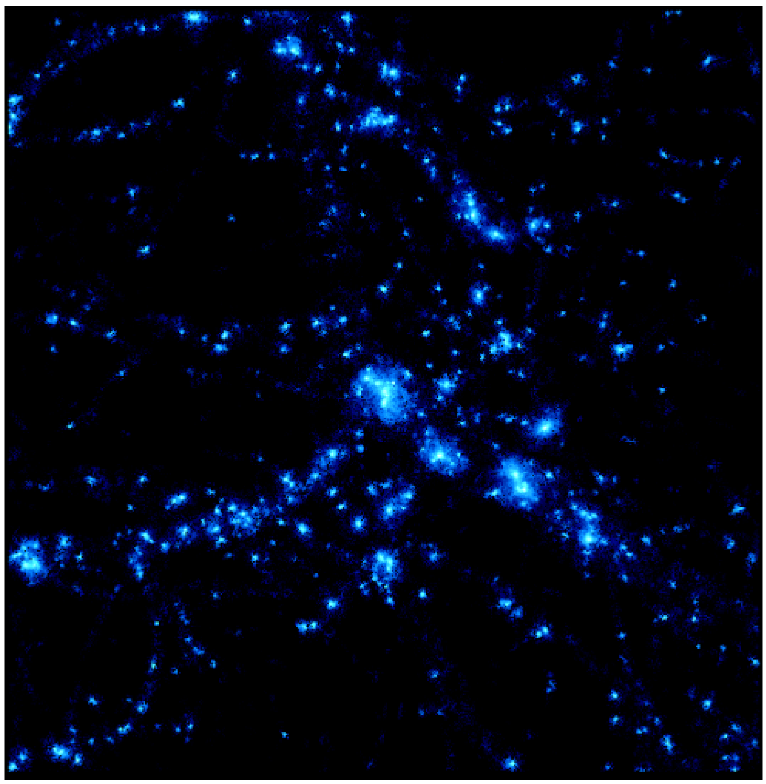
Radial Distribution



Progenitors at high redshifts are very biased

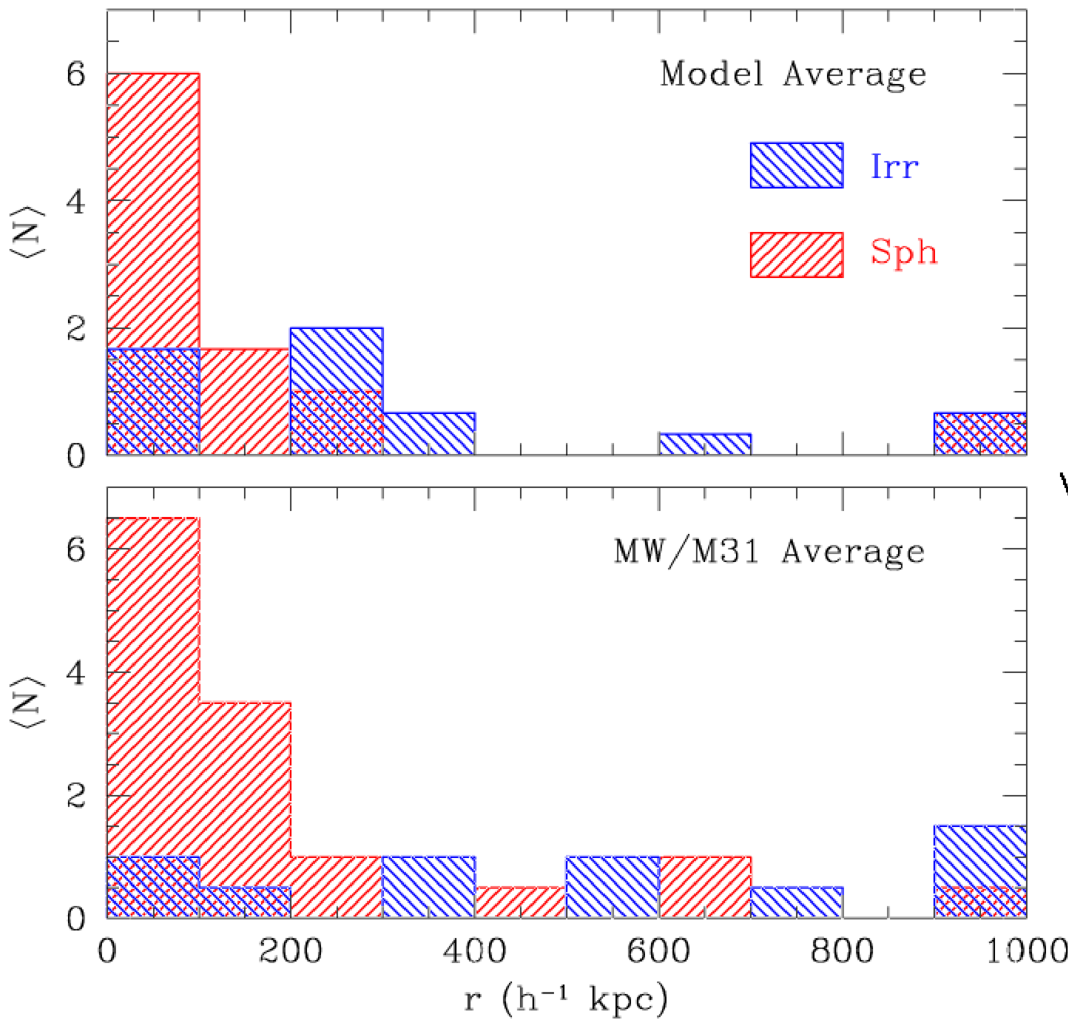


z = 0



z = 7

Morphological Segregation



Sph:

Vrot/σ <3

Other results

- ❑ Stellar masses of galaxies range from few x 10^5 Msun to 10^{10} Msun, consistent with the observed range.

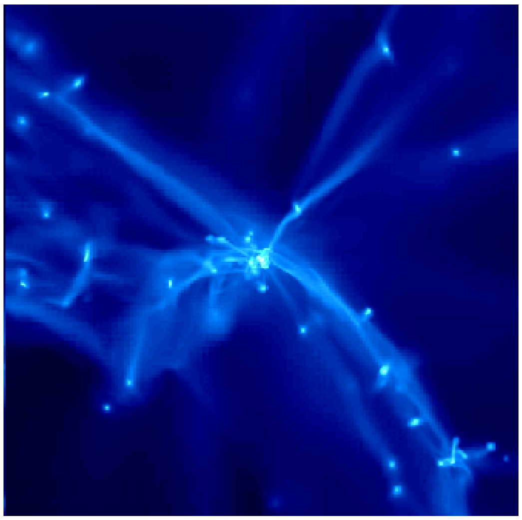
- ❑ Galaxies in the model exhibit a variety of star formation histories. Starformation is generally bursty. Most galaxies have initial burst at $z>4$. This in qualitative agreement with observations

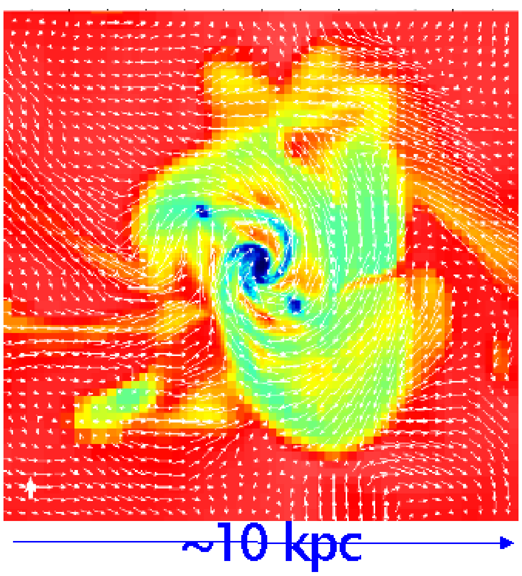
- ❑ The model reproduces the observed range of central stellar surface densities (~5- 50 Msun pc^{-2}) and dependence of surface density on stellar mass.

- ❑ Satellites located within 50 kpc of the host have typically higher stellar surface densities than the more distant systems.

- ❑ There is a population of dark starless subhalos that contain significant amount of gas. These could be counterparts of the observed compact high- velocity clouds.

Gasdynamics+DM simulations of a MW size system





Adaptive Refinement Tree (ART) code

Hydrodynamics: Eulerian Adaptive Mesh Refinement

N-body dynamics of DM and stellar particles

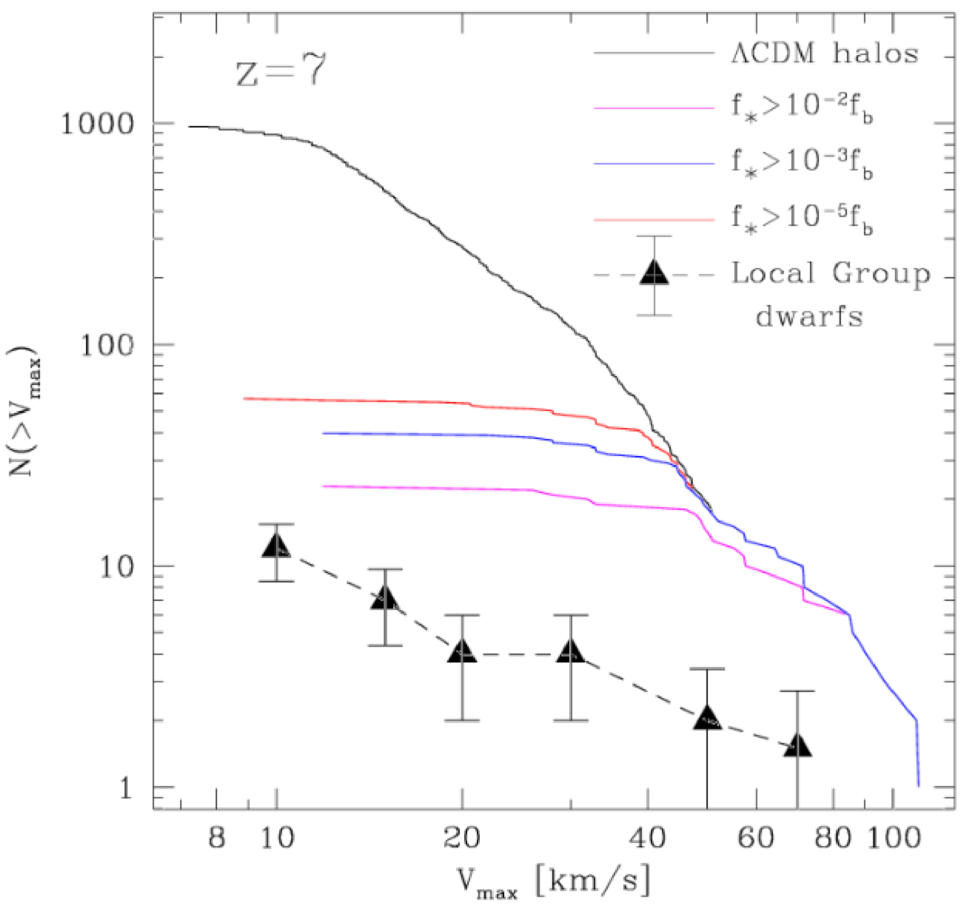
Cooling and heating: Compton, heating by the UV background, density and metallicity dependent net cooling/heating equilibrium rates taking into account line and molecular processes rates tabulated for $100 < T < 10^9$ K

Star formation using a phenomenological recipe
Thermal stellar feedback
Metal enrichment by SNII/Ia,
Stellar mass loss

Simulation followed formation of a MW-size galaxy at $z > 2$. A Lagrangian region corresponding to 5 Rvir of the object at z=0 was followed in a 6/h Mpc box

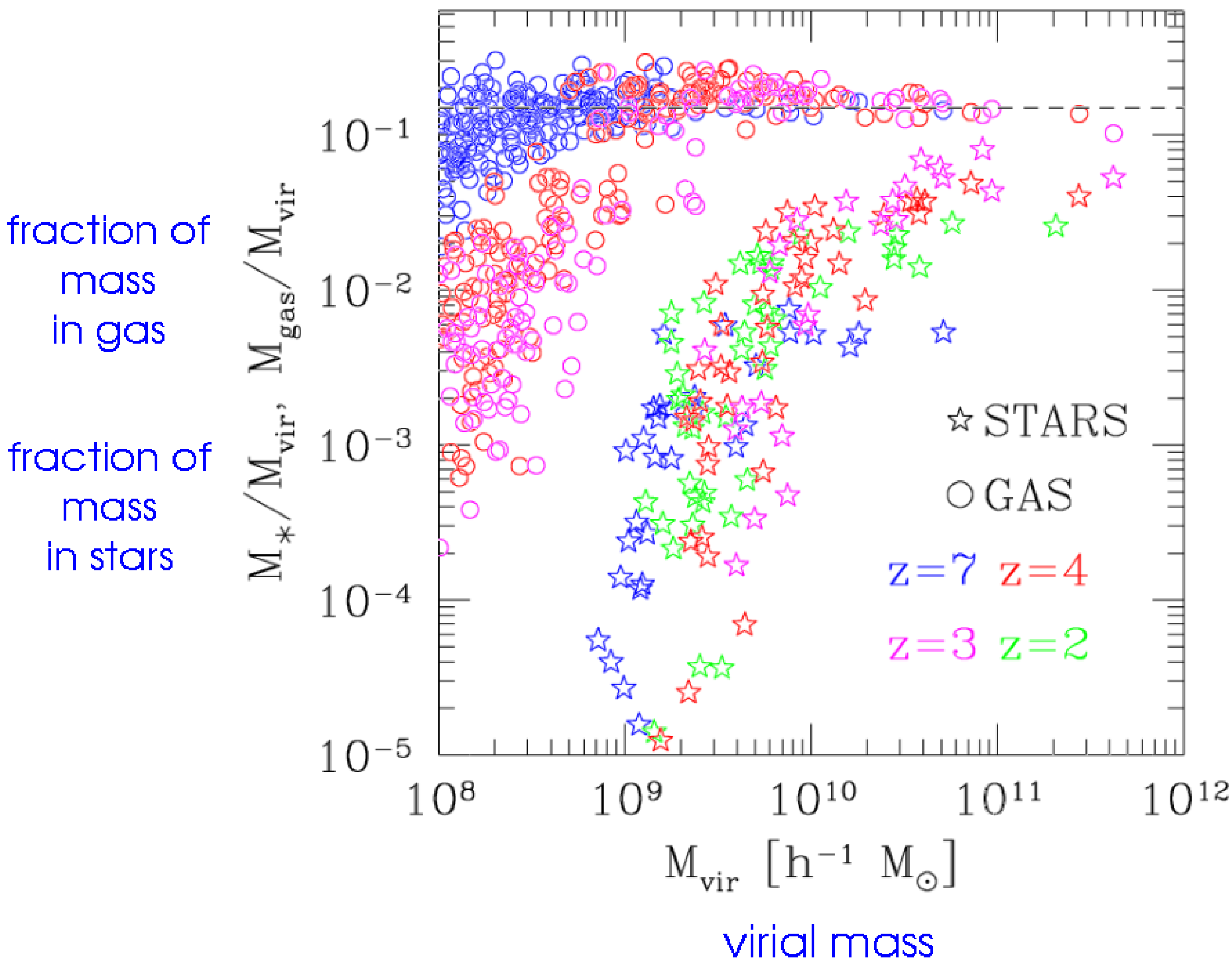
Peak resolution in this region was ~20 (10/(1+z)) pc
DMparticle mass ~10^6 Msun

Abundance of luminous dwarfs at z=7



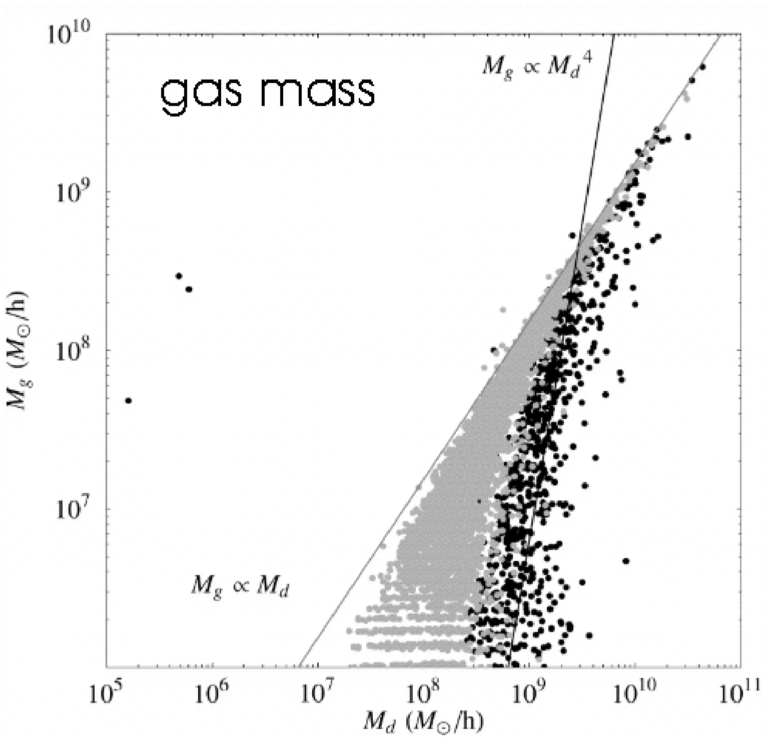
cumulative circular velocity function

What suppresses the star formation?

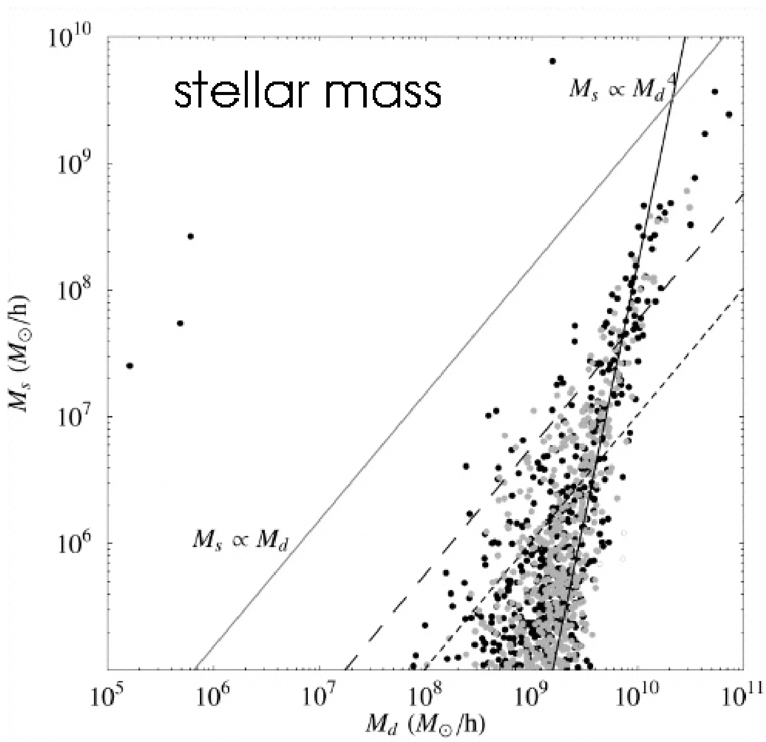


Chiu, Gnedin & Ostriker 2001, ApJ 563, 21

simulations with gasdynamics, radiative transfer, and non- equilibrium chemistry of H, He, H_2

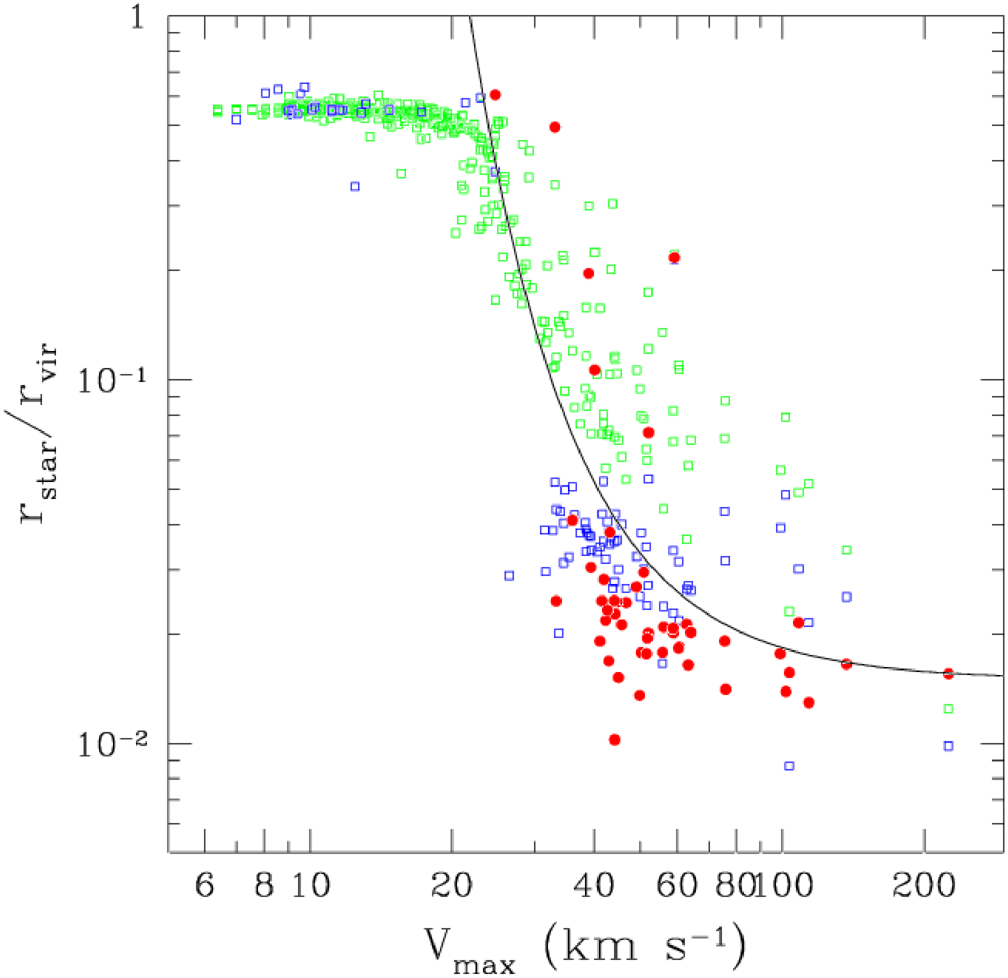


halo virial mass



halo virial mass

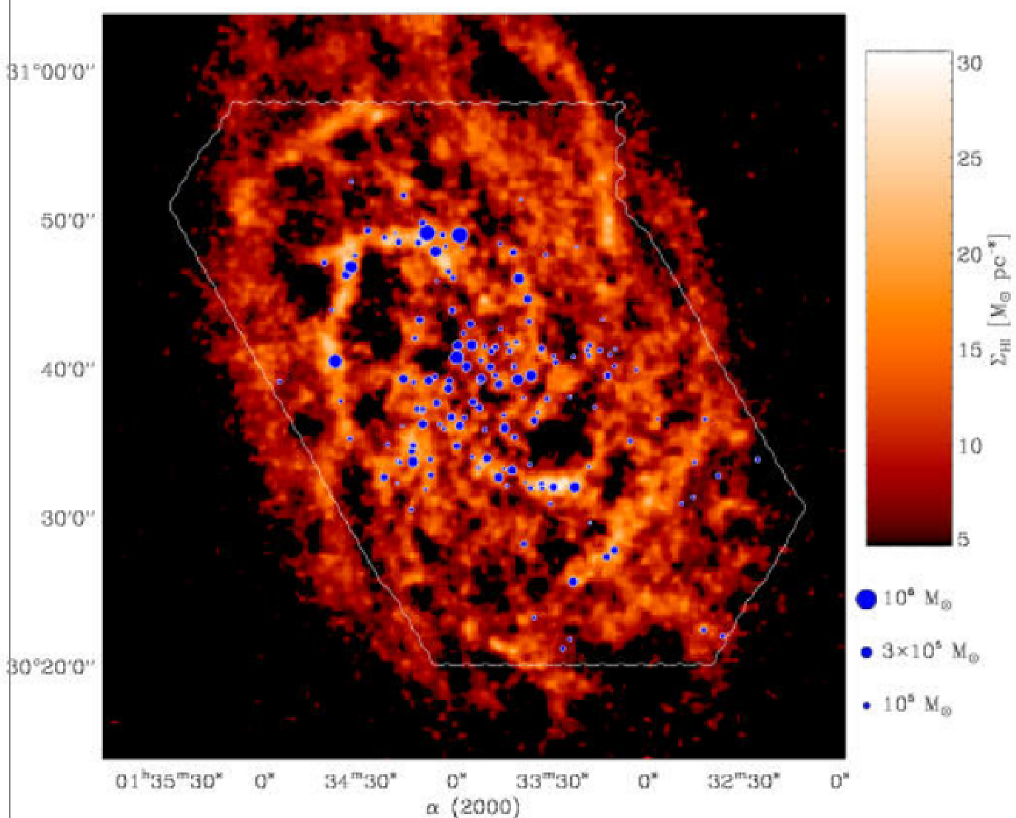
Inefficiency of gas cooling in dwarf halos



ratio of stellar extent to the halo extent

maximum circular velocity

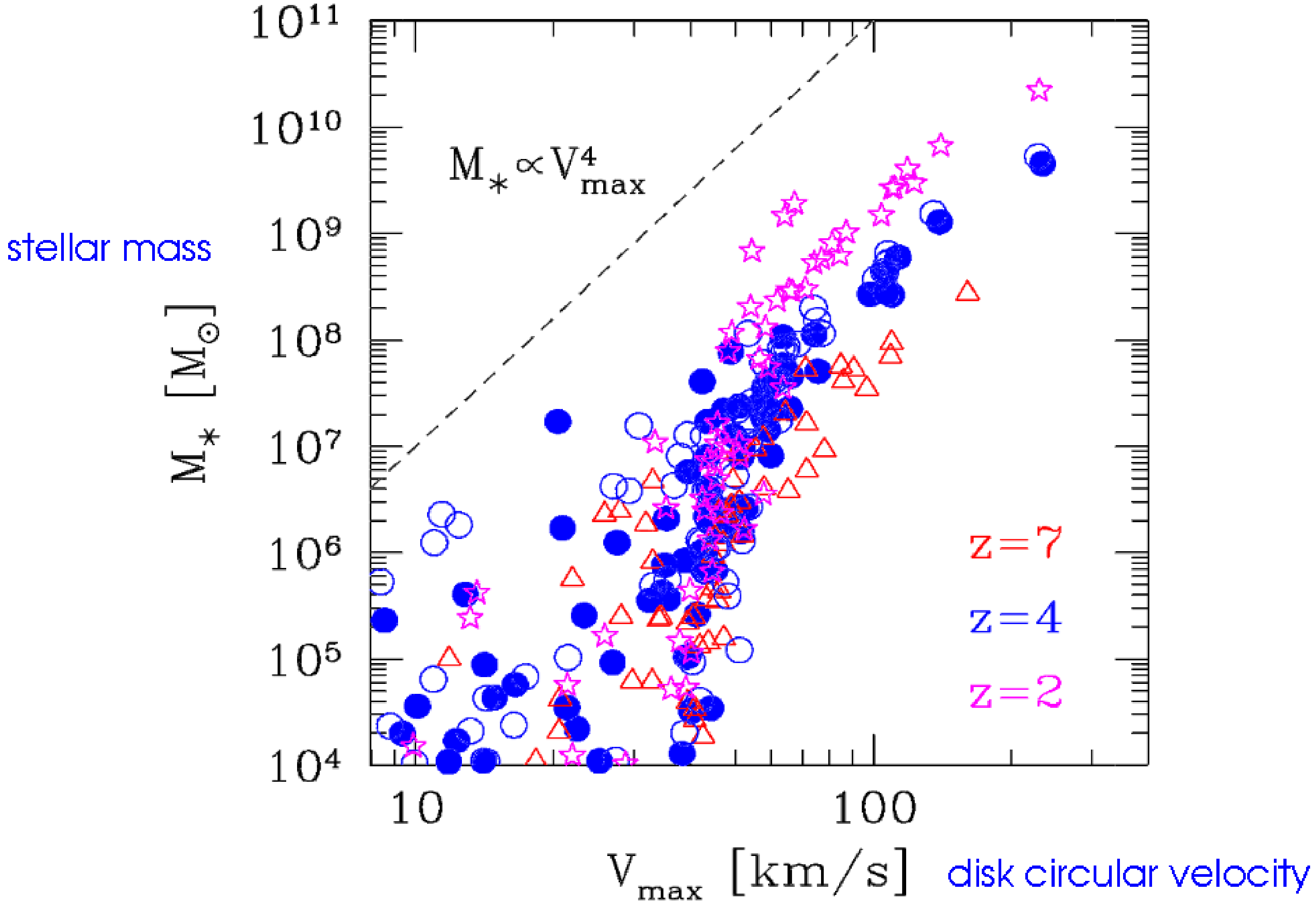
Presence of gas does not guarantee star formation



star formation in M33

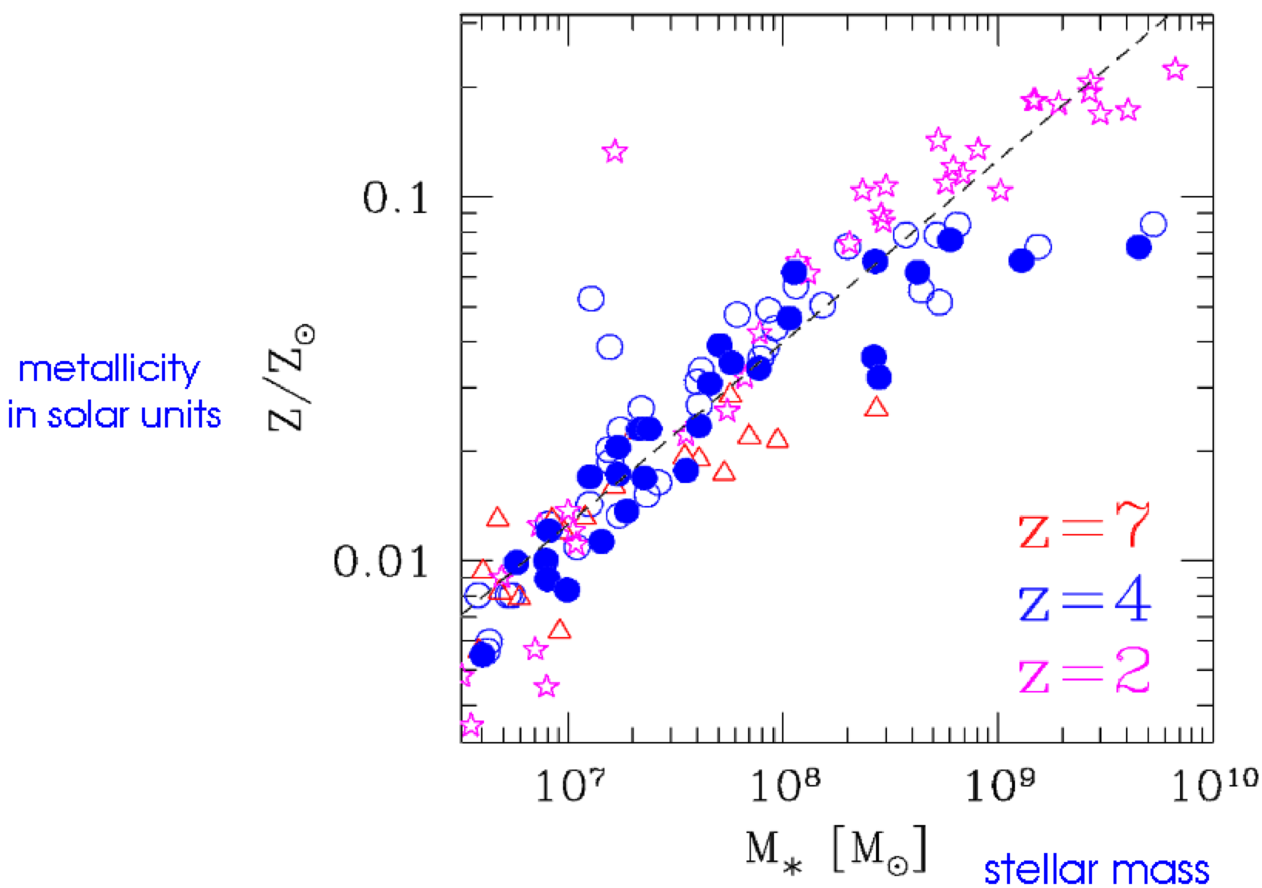
CO map: Blitz et al. 03; HI map: Deul & van der Hulst (1987)

Tully- Fisher relation



Metallicity- stellar mass correlation

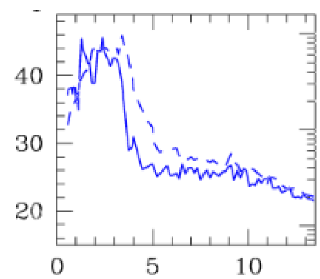
reproduced well in simulation but is not caused by energy feedback



Dekel & Woo 2002; correlation for the galaxies in the Local Group and SDSS

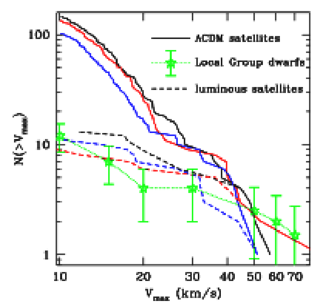
Summary

❑ Many galactic satellites have had tumultuous past. After initial stage of rapid mass growth they experience dramatic mass loss and shake- up of the internal structure due to tidal stripping.

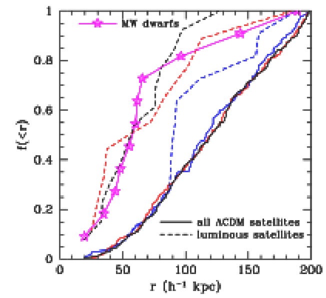


About 10% of the smallest dwarf satellites orbiting simulated galactic halos at z=0, have been ~10- 100 times more massive at some point in their past.

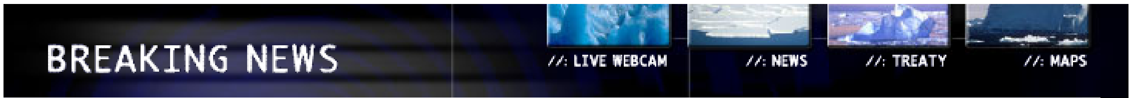
❑ This provides a simple explanation for why only ~10% of the small (Vmax < 30 km/s) satellite halos manage to become luminous.

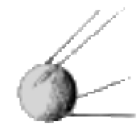


A simple galaxy formation model based on the evolutionary tracks extracted from simulations reproduces the abundance, radial distribution, and morphological segregation of galactic satellites



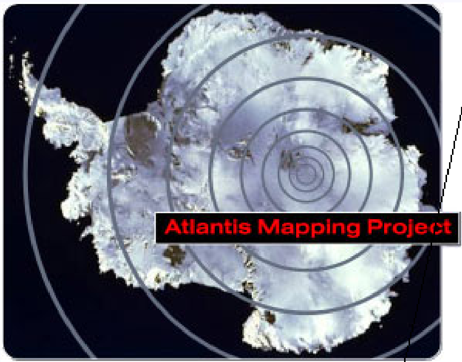
for details see: astro - ph/0401088





Wednesday, April 10, 2001
Web posted at: 5:25 a.m. EDT (0925 GMT)

Missing U.S. Spy Satellites Fuel Antarctica Suspicions



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WASHINGTON (AMP) — International observers say that three missing American spy satellites bolster Russian accusations that the United States is mounting a secret military expedition in Antarctica in violation of international law.

Russian scientists in March detected a "seismic event" in the vicinity of an alleged American military base in Antarctica just hours before a huge chunk of ice twice the size of Delaware broke off from the Ross Ice Shelf. (Seismic Map) The U.N. Security Council is trying to determine whether the U.S. is conducting nuclear tests in violation of the Antarctic Treaty — a charge the U.S. has denied.

Since the March 23 event, however, no known spy satellites have passed over the affected area. That suggests to some observers that one or more of the missing U.S. satellites may be watching.

"Three American spy satellites were launched from Vandenberg Air Force Base in California last year and disappeared after only a few weeks in their initial orbits," said one American scientist who spoke on condition of anonymity. "In fact, they may have been moved into secret orbits over Antarctica so they can carry out their covert

WASHINGTON (AMP) — International observers say that three missing American spy satellites bolster Russian accusations that the United States is mounting a secret military expedition in Antarctica in violation of international law.

Military strikes are usually mounted immec
before the enemy — or natural phenomen
the U.S. is merely tracking seismic events

The U.S. Air Force acknowledged the disa
malfunctioned and were destroyed. But er
skeptical.

"Dead U.S. spy satellites are usually left in orbit," said a systems engineer with Lockheed Martin Corp., which in 1998 saw one of its Titan 4A rockets self-destruct less than a minute after launch. The 20-story rocket was believed to be carrying a top-secret $1 billion spy satellite for the Air Force. "Furthermore, high-profile failures like this typically prompt protests from congressional leaders who monitor U.S. intelligence gathering. That has not happened."

Experts instead suggest the satellites were placed into orbits that would move them more slowly across the skies than other high-altitude spy cameras, giving them more time to photograph targets.

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